Validation of Broadband Ground Motion from Dynamic Rupture Simulations: towards better characterizing seismic hazard for engineering applications

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Project Objectives: Overview

In areas of infrequent seismicity or where geologic structures (e.g., sedimentary basins) complicate seismic wave propagation, earthquake ground motion simulations provide one approach to improving the accuracy of ground motion predictions for seismic hazard analyses. However, most current methods for simulating earthquake ground motions ignore important features of the earthquake rupture and typically employ stochastic approaches at frequencies above ~1 Hz. Here, we worked towards improving methods for simulating earthquake ground motions for seismic hazard applications by forming a group modeling effort that incorporates dynamic features of the earthquake fault and rupture (e.g., through complex fault geometry, stress heterogeneity, etc…) that have been demonstrated from both observations and numerical simulations to affect resulting ground motions.

The work was carried out by first creating a database of dynamic rupture simulations (a fully deterministic, physics-based approach) of strike-slip earthquake mechanisms at frequencies computationally accurate up to ~3 Hz (and higher where computationally feasible). The resulting broadband ground motions were evaluated (validated) by comparing with trends predicted by leading empirical ground motion models (GMMs). We focused on a narrow magnitude range (Mw 6-7) at near-fault distances (within 20 km from the source), comparing median spectral accelerations across a range of spectral periods. Additionally, we analyzed the synthetic ground motion variability (as computed in terms of intra-event residuals) as a function of both distance and period.

One of the project's larger visions is to build a synthetic database of ground motion amplitudes from a diverse range of initial conditions and modeling techniques. Additionally, we also keep track of final fault displacement along the surface trace of the fault, for future evaluation by another SCEC project team. In the future, we intend to make our database publicly available, for use by a variety of end-users and investigators. For example, it's likely a few of our simulated events will have similar characteristics to recently recorded events (e.g. the Ridgecrest sequence), that may be used for additional validation and constraint of both surface slip and ground motion amplitudes.

Background

Deterministic simulations allow one to generate synthetic ground motion of both historical and hypothetical events and to perform analysis of the resulting ground motion using a user-defined station distribution. Broadband hybrid techniques have been developed that combine low-frequency deterministic ground motion with stochastically generated high-frequency components (e.g. Hartzell et al., 2005; Mai et al., 2010; Graves and Pitarka, 2010); for example, as used in the SCEC broadband platform validation project. These techniques, however, typically lack deterministic information at higher frequencies that may be important in predicting strong ground motion. Dynamic ruptures, on the other hand, are a more physically realistic way to model earthquake rupture; the initial stress conditions and a friction law are imposed along the fault interface, and the earthquake rupture proceeds according to the physical equations governing the problem.

Deterministic approaches have been used at low frequencies (< ~1 Hz) for many years; only recently has there been the computational ability to simulate 3D deterministic high-frequency earthquake ground motion at significant distances from the source. Recent efforts have extended deterministic simulations to higher frequencies, using purely physics-based simulations (Taborda et al., 2016; Roten et al., 2016; Graves and Pitarka, 2016; Andrews and Ma, 2016; Mai et al., 2017; Withers, 2018a,Withers, 2018b), crucial to better determining the seismic hazard associated with the largest portion of engineering structure portfolios that typically have a resonance frequency larger than 1 Hz. To produce realistic ground motion at these higher frequencies, the source and surrounding medium need to be defined in sufficient detail to model the high-frequency synthetics accurately. This includes ensuring that the source has energy content comparable to observations as well as incorporating complex velocity structure.

The kinematic approach has previously been validated using global GMMs (for example, the SCEC Broadband Platform project: Goulet et al, 2015). There have also been several studies that performed dynamic rupture model validations in a statistical sense using reference global empirical GMMs models (e.g. Ripperger et al., 2008; Baumann and Dalguer, 2014; Andrews and Ma, 2016; Shi and Day, 2013; Withers et al., 2018a,b). Most of these studies, however, focused on a single scenario event (and in some cases where the GMMs are not well constrained) and researchers have yet to validate their respective approaches across a range of magnitudes.

Methodology: Research Approach
In this project, we aim to generate earthquake sources that produce synthetic ground motion across a wide bandwidth for magnitudes and distances relevant to engineering applications, for which empirical datasets are still poorly populated. This is a long-term endeavour, but we have made substantial progress this year. We worked towards validating ground motions produced by dynamic rupture models against the empirical trends of GMMs. We simulated a suite of events up to Mw 7 along strike-slip earthquakes and generated synthetic ground motion up to 20 km from the fault. Within each magnitude bin, we included multiple variations of initial stress conditions and hypocenter locations, so as to sample a range of earthquake rupture conditions. We follow a similar approach to the "Part B" validation of the SCEC Broadband Simulation Platform (Goulet et al., 2015), where pseudospectral acceleration (PSA) from GMMs was analyzed at various magnitudes and closest distance (R_{rup}). We initially keep the medium simple— using a 1D layered model (characteristic of a California hard-rock site, with a V_{S30} of 760 m/s) and analyze the variability of the synthetic ground motions (arguably a proxy for single-station standard deviation). This project leverages the PI's expertise and computational infrastructure developed in past years; each of the codes used here have performed well in the SCEC/USGS Dynamic Rupture Code Verification Project (Harris et al., 2018).

There are several approaches to specify random distributions of fault stress, frictional properties, and/or fault roughness input into the simulations to produce variations in magnitude and distribution of ruptures (and that match observation data of spectral energy across a range of frequencies). We pursued two main routes of rupture variation: (1) imposing stochastic conditions along a planar fault with heterogeneous stress or friction conditions and (2) generating fractal rough-faults, where homogenous background stress conditions naturally introduce initial heterogenous stress along the fault. Both techniques have been used successfully in previous work to generate ground motion that compares favorably with GMMs. For example, Andrews and Ma (2016) used a modified method of Andrews and Barall (2011), where the initial stress condition along a planar fault was heterogenous. An example of a rough-fault geometry study is Withers et al. (2018b), where dynamic rupture simulations were run along rough faults matching the fault dimensions of the Northridge event. The local variations in strike and dip produced heterogeneity in the regional stress field when rotated onto the fault, promoting or impeding rupture across many scale lengths, leading to realistic ground motion intensities across a wide range of frequencies and shown to compare well with GMM results.

Results: 2019 SCEC Summary of Work

Our group is the first coordinated validation effort to model ground motions from dynamic ruptures, encompassing a wide level of well qualified individuals across all stages of career and background. We setup a regular routine of bi-weekly conference call to coordinate and discuss science ideas, progress updates, and practical issues of validation. We quickly discovered that the initial breadth of the original project plan needed adjustment to match each team's limitations, both from a code perspective and computational constraints. We thus refined our focus to modeling strike-slip earthquakes up to Mw7 and generating ground motions up to 3 Hz.

Our first step was to define a "benchmark" consisting of a strike-slip fault set in a defined velocity structure. The benchmark parameters are shared via a dynamic web document that each modeler can reference in setting up their model. We chose a model domain that included the closest distance to rupture up to 20 km, far enough from the source to be able to evaluate distance trends, but small enough to limit the effect of path effects not modeled with the simple 1D velocity medium and computational limitations. This has the advantage to allow our group to focus on source effects rather than on path or site effects. The source is centered in the model domain, to allow symmetric evaluation of ground motion at all azimuths. Both means and standard deviations of intensity measures from multiple realizations were targeted to be output and compared with GMMs.

The value of working within a coordinated team is to develop different approaches for the prescription of model characteristics that lead to validated ground motions. In that spirit, each co-PI constructed models of the benchmark by using their own preferred technique in specifying initial stochastic stress conditions, fault friction properties or geometrical fault complexity. They each developed a distribution of events by running a suite of dynamic rupture simulations appropriate within the magnitude range Mw 6–7, computationally accurate to frequencies ranging from 0.1 up to ~3 Hz. The following list outlines each PI's technique used to simulate a distribution of ruptures and describes their chosen method.

Withers constructed models with stochastic fault roughness and ran spontaneous earthquake ruptures along rough-faults, using a well-verified code (Waveqlab3D) that accurately simulates the rupture along a fault with geometrical complexity at both short and long wavelengths. A suite of simulations was developed for validation by varying the random seed of the rough-fault geometry; this naturally produces varying magnitude events with variation of the hypocentral location and background stress conditions. Figure 1 shows an example of three realizations of ruptures along one rough-fault topography profile, with variations in hypocenter location, as well as final slip and stress drop along the fault.

Ma's group extended the heterogeneous stress model of Andrews and Ma (2016) (that leads to self-similar stress drops) to M6.0 vertical strike-slip events during the last year. They fixed the rupture length to 20 km along strike and buried the rupture to 5 – 10 km depths. In this method, the long-wavelength along strike determines the amplitudes of all other shorter wavelengths, allowing ruptures to die out naturally. They simulated dynamic rupture and ground motion at 21 stations in 10 km off the fault (Figure 2).

Ampuero's group developed and tested models with heterogeneous fault stresses constructed as the superposition of residual stresses left by previous ruptures, whose spatial density and size distribution is consistent with the statistics of background seismicity. Further guidance on model parameterization was derived from earthquake cycle simulations on heterogeneous faults. Theory and exploratory 2D simulations showed that residual stress concentrations efficiently produced rupture speed variability and pulse-like rupture that enriches the high-frequency radiation. Figure 3 shows the creation of a set of past events used to compute stress drop increases along the fault plane. Fig 3(a) shows the distribution of event magnitudes, designed according to the regional Gutenberg-Richter distribution for a target event of magnitude 7 (considering b=0.95). Figure 3 (b) and (c) display the spatial distribution of the event ruptures and consequent horizontal shear stress, assuming a constant normal stress of 100 MPa and an S ratio of 2 (corresponding to a subshear rupture velocity). Figure 3(d) and (e) plot final slip and rupture time on the fault plane resulting from 3D SEM simulation. Nucleation in the middle of the fault triggers rupture in weaker zones (borders of past events) and results in slip heterogeneity, as expected.

Results from the team. We compared our synthetically generated ground motions with current state-of-the art GMMs (including Boore et al., 2014, Abrahamson et al., 2014, Campbell & Bozorgnia, 2014, and Chiou & Youngs, 2014). Figure 2 shows an example of ground motion for two random realizations by Ma compared to Boore et al. (2014). The mean and standard deviation at high frequencies are found to be underestimated, compared to the GMM. In order to better match GMM results, the rupture needs to come very close to the free surface, which may be unrealistic for M 6.0 earthquakes. Therefore, the method may need be improved to simulate buried ruptures, which was proposed as part of continuing work for 2020.

Figure 4 shows an example comparison of a set of simulations that varied hypocenter location along a rough-fault profile. Here, we found that the overall level of ground motion compares well with GMM's predictions (distance and period dependence), and that the intra-event variability is highly dependent on hypocenter location, resulting from azimuthal changes in ground motion amplifications. The overall level of variability is lower, as expected, since we currently exclude site effects and full 3D heterogeneity in our velocity model.

In addition to modeling ground motion, we also keep track of fault displacement along the surface trace of the fault. Modelling fault displacement in parallel with ground motion ensures that we don't create unrealistic source events that may neglect constraints of rupture, a possibility if efforts of source generation are pursued in isolation. This database is leveraged in an ongoing companion research project of validation of fault displacement from dynamic ruptures by a subset of our group (primarily Wang, Dalguer and Goulet).

We presented our results at the annual 2019 SCEC annual meeting and updated progress at the 2019 AGU meeting. We have benefited from suggestions from the community and have received significant interest in both the effort and results, including making the database available to the public for further investigation.

Summary

This year was the beginning of a newly formed SCEC-funded project that focused on a collaborative approach to validation of ground motions produced from dynamic rupture simulations. We worked towards improving models of earthquake rupture for applications to seismic hazard. Here, we utilize a dynamic rupture approach to validate synthetically generated ground motion by comparing with GMMs at a range of magnitudes and distances of engineering relevance. Our method uses physics-based simulations to generate deterministic broadband ground motions; the synthetic median and variability of our simulations are compared with leading ground motion models (GMMs). Our goal is to address relevant needs of the community, particularly the end users of simulations such as engineering researchers and engineers. We intend to make our validation benchmarks publication available to the community, so that individuals from a variety of background disciplines can leverage our results for a variety of purposes.

This propose leveraged each PI's expertise and computational infrastructure developed in past years; each of the codes proposed here have performed well in the SCEC/USGS Dynamic Rupture Code Verification Project (Harris et al., 2018) and each modeler now has access to large-scale supercomputing allocations.

This work was the first step of a planned multi-year project. Next, we plan to continue to simulate ruptures, with a diverse distribution of initial hypocenter locations, initial background stress and friction conditions, and varying modelling approaches, including varying fault geometry and heterogenous stress distributions. This will provide a database large enough to perform a statistical analysis on, allowing determination of outliers, average trends, and uncertainty levels.

In the future, we envision selecting a few key representative historical earthquakes from the SCEC Broadband Simulation Platform (Goulet et al., 2015) that will be used to further ensure that the ground motion is consistent with that of strong ground motions records. Additionally, validation will be extended to include more complex events, such as both normal and reverse earthquake mechanisms, and iteratively expand the range of model parameters, domain size, and upper frequency limit so as to provide validated methods representing realistic conditions. If these initial validation efforts are satisfactory, we plan to begin the process of going beyond the GMMs to demonstrate that dynamic rupture simulations have the potential to provide more information to inform seismic hazard for engineering applications.

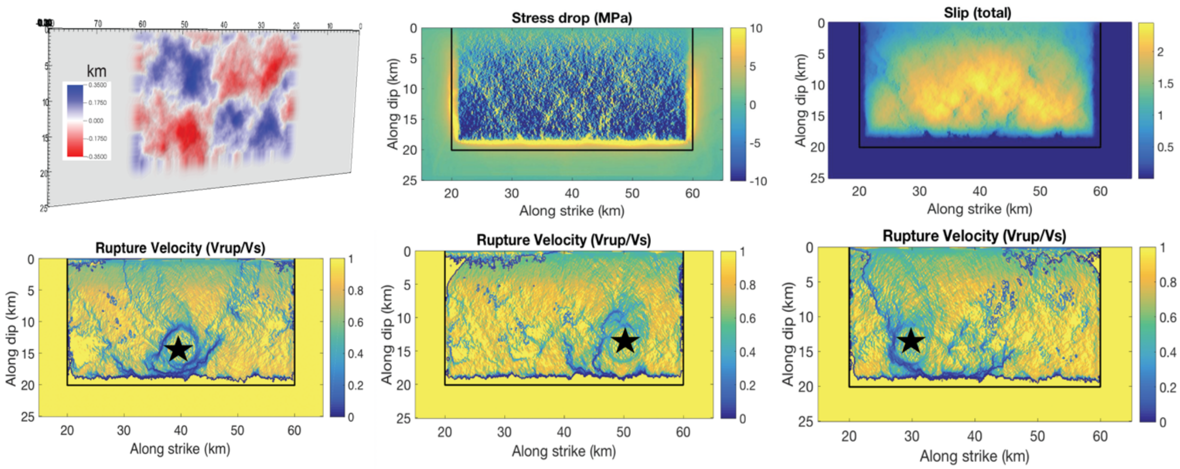

Figure 1. Three example dynamic rupture simulations highlighting the different rupture behavior for 3 hypocenter locations along a rough-fault, keeping other initial parameters the same. Nucleation is achieved by a forced rupture in a small region (radius of~3 km) surrounding the chosen hypocenter location. (Top) Rough-fault geometry, stress-drop and final slip for an example simulation. (Bottom) Rupture velocity is heterogenous, due to geometry and stress-conditions. (from Withers et al., 2019).

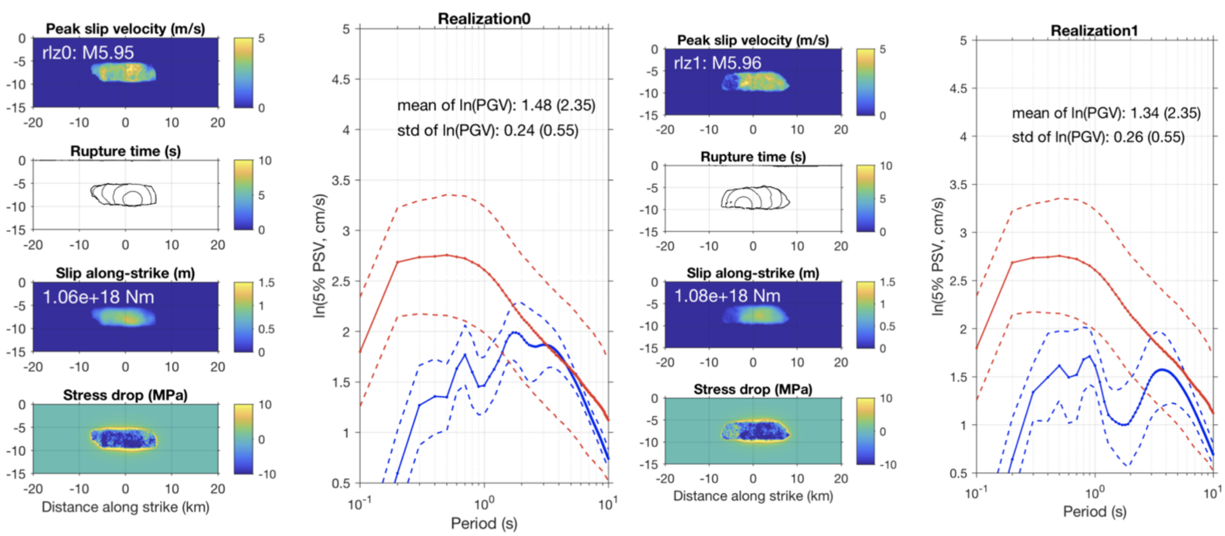

Figure 2. Results for two realizations of a M_W 6.0 earthquake showing peak slip velocity, rupture time, slip, and stress drop on the fault. The magnitude and moment of each realization are also shown. In the right panel of each realization, the peak ground velocity (PGV) and 5% damped pseudospectral velocity (PSV) at 21 stations uniformly distributed between -10 km and 10 km along strike at 10 km off the fault (blue) are compared with those of the GMPE (red). The dashed line shows one within-event standard deviation. The mean and standard deviation of logarithm of PGV (cm/s) of each realization are shown in each panel (the first row is the mean and second row the standard deviation). The numbers in the parenthesis are those of the GMPE.

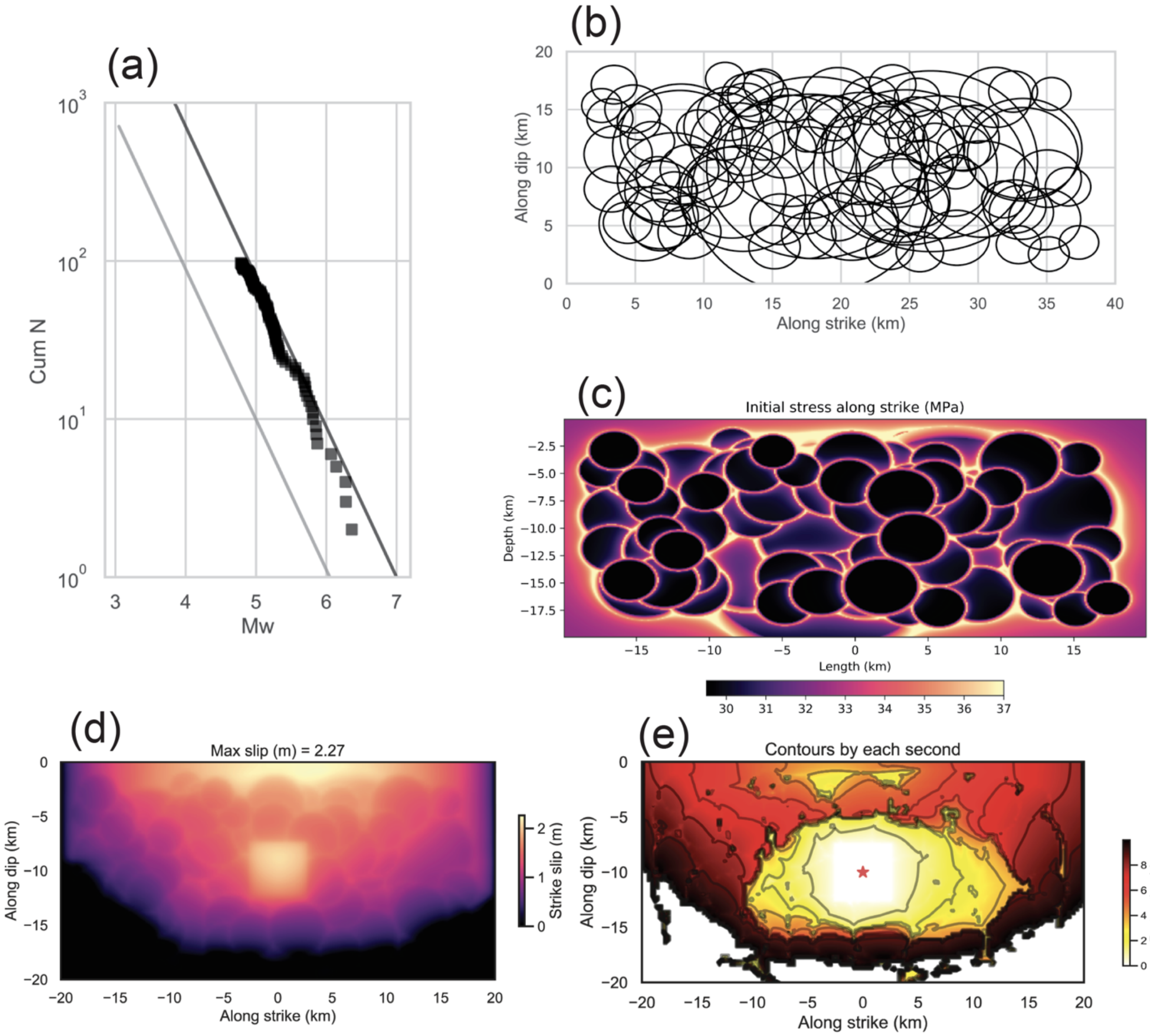

Figure 3. We created a set of past events and used each of the events to compute stress changes on the fault plane. (a) Distribution of event magnitudes. It respects the regional Gutenberg-Richter distribution for a target event of magnitude 7 (considering b=0.95). (b) and (c) display the spatial distribution of the event ruptures and resulting horizontal shear stress when normal stress is assumed to be constant and equal to 100 MPa (S parameter corresponds to 2). (d) Final slip and (e) rupture time on the fault plane computed by 3D SEM simulation.

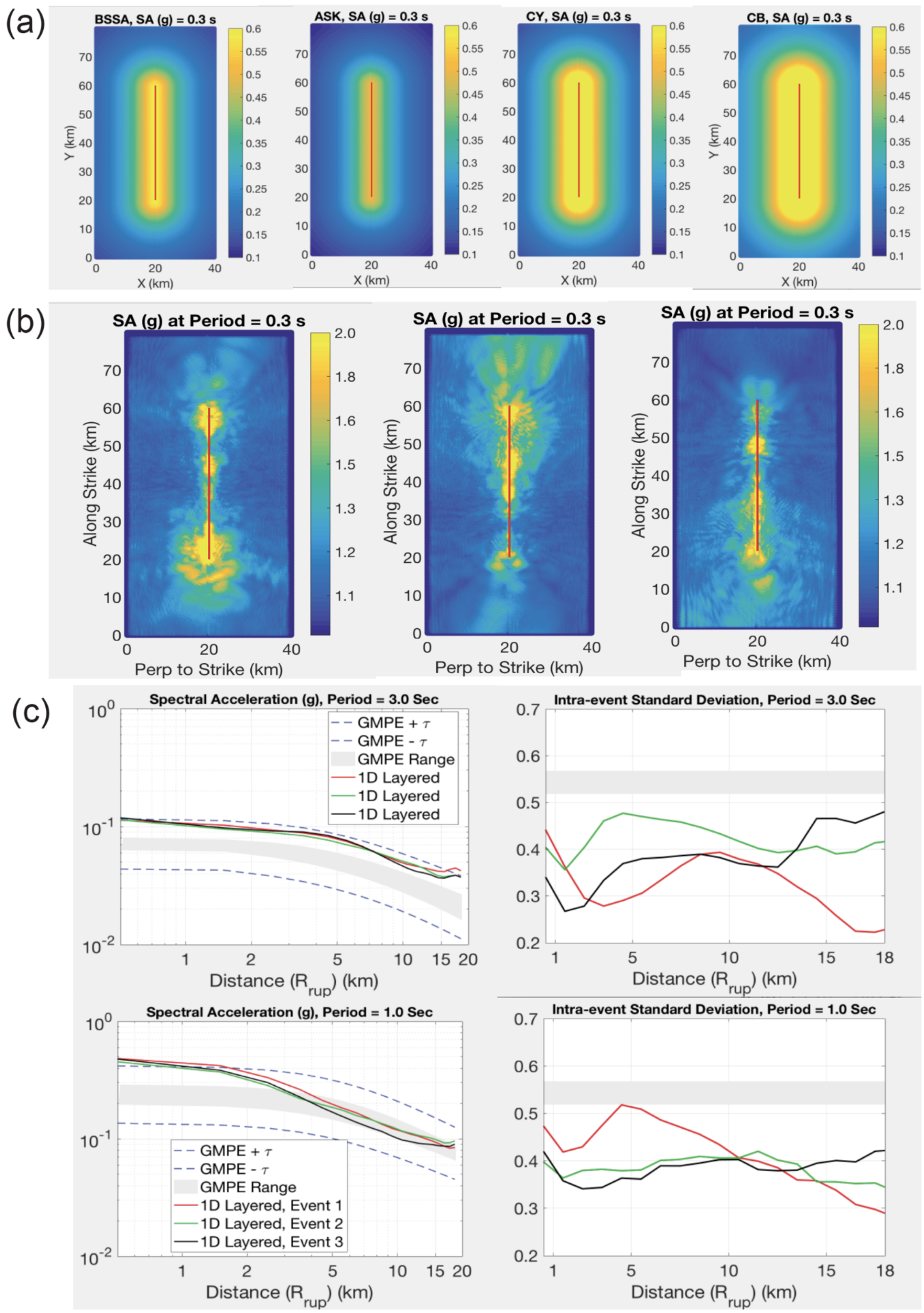
(a)
BSSA, SA (g) = 0.3 s
ASK, SA (g) = 0.3 s
CY, SA (g) = 0.3 s
CB, SA (g) = 0.3 s
Y (km)
X (km)
(b)
SA (g) at Period = 0.3 s
Along Strike (km)
Perp to Strike (km)
(c)
Spectral Acceleration (g), Period = 3.0 Sec
GMPE + τ
GMPE - τ
GMPE Range
1D Layered
1D Layered
1D Layered
Distance (Rrup) (km)
Intra-event Standard Deviation, Period = 3.0 Sec
Spectral Acceleration (g), Period = 1.0 Sec
GMPE + τ
GMPE - τ
GMPE Range
1D Layered, Event 1
1D Layered, Event 2
1D Layered, Event 3
Intra-event Standard Deviation, Period = 1.0 Sec

Figure 4. We extract ground motion from 4 leading GMPE relations (Abrahamson et al., 2014; Campbell and Bozorgnia, 2014; Chiou and Youngs, 2014; Boore et al., 2015) using the values of Z1.0, Z2.5, Vs30, Rjb, etc... used in our simulations. (a) An example extraction of SARotD50 at 0.3 s period. (b) Map-view plots of spectral acceleration (0.3 s) over the simulation domain, corresponding to hypocenter locations shown in (a) (c-Left) The spectral acceleration median (GMRotD50) at 1- and 3-seconds period as a function of distance for three ruptures with varying hypocenter locations. The shaded region indicates the range of the four GMM medians, where the dashed lines are the ±1 interevent standard deviations. (c-Right) Intra-event standard deviations as a function of distance, with the shaded area indicating the intra-event standard deviation range of the four 2014 GMM models. Note the linear display in the distance along the abscissa (from Withers et al., 2019).

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